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Stabilization of swine wastes: A systematic review of its environmental impact and technological alternatives

Estabilização de dejetos de suínos: Uma revisão sistemática do seu impacto ambiental e das alternativas tecnológicas

Estabilización de desechos porcinos: Una revisión sistemática de su impacto ambiental y alternativas tecnológicas

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Abstract
The inadequate management of swine fecal waste endangers human health and the environment, causing soil contamination, the spread of zoonoses, and eutrophication of water bodies. These nutrient-rich wastes also contain antibiotic resistance genes (ARGs), posing a significant public health risk. This systematic review aims to identify optimal operating parameters for stabilizing pig waste, focusing on the production of compost, biosolids and biogas, while taking into account the specific composition of these wastes. Operational parameters for waste stabilization, including composting, and biogas generation, are analyzed. The findings aim to identify issues and propose solutions for a more sustainable and efficient management of these wastes, thereby protecting the environment and public health.
Keywords: Swine Manure; Swine Slurry; Composting; Biogas; Anaerobic; Co-Digestion.

Resumo
O gerenciamento inadequado de resíduos fecais suínos coloca em risco a saúde humana e o meio ambiente, causando contaminação do solo, disseminação de zoonoses e eutrofização de corpos d'água. Esses resíduos ricos em nutrientes também contêm genes de resistência a antibióticos (ARGs), representando um risco significativo à saúde pública. Esta revisão sistemática visa identificar parâmetros operacionais ideais para estabilizar resíduos suínos, com foco na produção de composto, biossólidos e biogás, levando em consideração a composição específica desses resíduos. Parâmetros operacionais para estabilização de resíduos, incluindo compostagem e geração de biogás, são analisados. As descobertas visam identificar problemas e propor soluções para um gerenciamento mais sustentável e eficiente desses resíduos, protegendo assim o meio ambiente e a saúde pública.
Palavras-chave: Dejetos de Suínos; Esterco de Suínos; Compostagem; Biogás; Anaeróbio; Co-Digestão.

Resumen
El manejo inadecuado de los desechos fecales porcinos pone en peligro la salud humana y el medio ambiente, provocando la contaminación del suelo, la propagación de zoonosis y la eutrofización de los cuerpos de agua. Estos desechos ricos en nutrientes también contienen genes de resistencia a los antibióticos (ARG), lo que supone un importante riesgo para la salud pública. Esta revisión sistemática tiene como objetivo identificar los parámetros operativos óptimos para la estabilización de los desechos porcinos, centrándose en la producción de compost, biosólidos y biogás, teniendo en cuenta la composición específica de estos desechos. Se analizan los parámetros operativos para la estabilización de los desechos, incluido el compostaje y la generación de biogás. Los hallazgos tienen como objetivo identificar problemas y proponer soluciones para una gestión más sostenible y eficiente de estos desechos, protegiendo así el medio ambiente y la salud pública.
Palabras clave: Estiércol Porcino; Purines Porcinos; Compostaje; Biogás; Anaeróbico; Codigestión.

1. Introduction

The inadequate management of swine fecal waste contaminates natural resources and threatens human health and the environment, particularly in regions with limited water access. This mismanagement contributes to increased soil contamination, spread of zoonoses, nutrient leaching, and eutrophication of water bodies (Fernández-Labrada et al., 2023; Gao et al., 2023). Swine slurry, a liquid mixture of excrement and urine produced in intensive livestock farming, is particularly rich in essential nutrients such as nitrogen, phosphorus, and potassium, making it a valuable fertilizer for agricultural soils (Duerschner et al., 2020). However, improper handling of swine slurry can lead to the spread of pathogens, affecting biodiversity and public health (Deng et al., 2023; Varma et al., 2021). Additionally, there is a high prevalence of antibiotic resistance genes (ARGs) in swine waste, with up to 90% of bacteria such as Proteobacteria, Actinobacteria, and Acidobacteria carrying these genes, posing a global concern for antimicrobial resistance (Sanz et al., 2021; Wang et al., 2023). Antibiotic-resistant bacteria (ARB) present in these wastes can migrate to adjacent soils and water bodies, significantly increasing public health risks. This underscores the need for a more integrated approach to managing swine waste at both local and global levels (Van Epps & Blaney, 2016; Couch et al., 2019; Yang et al., 2020). With the growing scarcity of freshwater exacerbated by climate change, managing the waste generated by intensive swine production, especially in countries like China, the United States, and the European Union, emerges as an urgent global challenge, given the daily production of millions of tons of fecal waste (FAO, 2022).

To address this environmental issue, stabilization technologies have been developed to recover high levels of organic matter, nitrogen, and phosphorus present in these wastes, transforming them into valuable products and significantly reducing the ecological impact of the swine industry. These technologies are classified into three categories: physical, chemical, and biological. Physico-chemical methods, such as coagulation and crystallization, are effective in separating and precipitating contaminants, as well as recovering nutrients from slurry (Chen et al., 2024; García-Valero et al., 2024). Among the biological processes, anaerobic digestion and composting stand out for their ability to transform organic waste into biogas and generate digestate, a biofertilizer rich in N, P, and K, used in agriculture (Meng et al., 2023; Montalvo et al., 2020). However, their large-scale implementation for the valorization of swine slurry is associated with high costs (González et al., 2020). Additionally, the biological processes used in the treatment of swine waste present engineering challenges due to their sensitivity to climatic conditions and slow microbial kinetics, which increase the size and cost of reactors, generate bad odors, and require constant maintenance (Lourinho et al., 2020; Myers et al., 2023). Given these scenarios, it is essential to complement biological processes with physico-chemical treatments, such as coagulation-flocculation, to improve the management of swine waste.

The physico-chemical characterization of swine waste is essential for optimizing its use in biological processes, as it allows for the identification of the need to add nutrients or co-substrates that enhance reaction kinetics and achieve high biological digestion. Detailed knowledge of the operational conditions required for these processes is essential. Furthermore, assessing the presence of ARB in swine waste and implementing effective treatments to eliminate them is critical to mitigating environmental and public health risks. This systematic review aims to identify the optimal operational parameters for stabilizing swine waste, with a focus on the production of compost, biosolids, and biogas, while accounting for the specific composition of these wastes.The contributions of this work include (i) the characterization of swine waste and (ii) the analysis of different stabilization processes. This approach identifies key issues and proposes solutions to improve large-scale waste management, fostering sustainability and environmental protection

2. Materials and Methods

This systematic review focuses on the treatment of swine waste, emphasizing the importance of raw material characteristics and pretreatment methods in influencing the stability of stabilization and digestion processes. Data collection was conducted through a comprehensive search of the Scopus database using the following keywords: ("swine manure OR slurry OR pig") AND ("composting" OR "co-digestion" OR "stabilization" OR "biogas"). The selection of studies adhered to the standards outlined in the PRISMA guidelines for systematic reviews and meta-analyses (Page et al., 2021; Chuenchart et al., 2024).

To ensure the quality of information, the review focused on open-access scientific articles published in English and indexed in high-impact journals. The search targeted studies that provided physicochemical and biological characterization of swine waste (both liquid and solid) and evaluated operational parameters for stabilization processes aimed at compost and biogas production. Excluded from the analysis were theses, qualitative studies, and research with incomplete data or those failing to meet rigorous methodological standards.

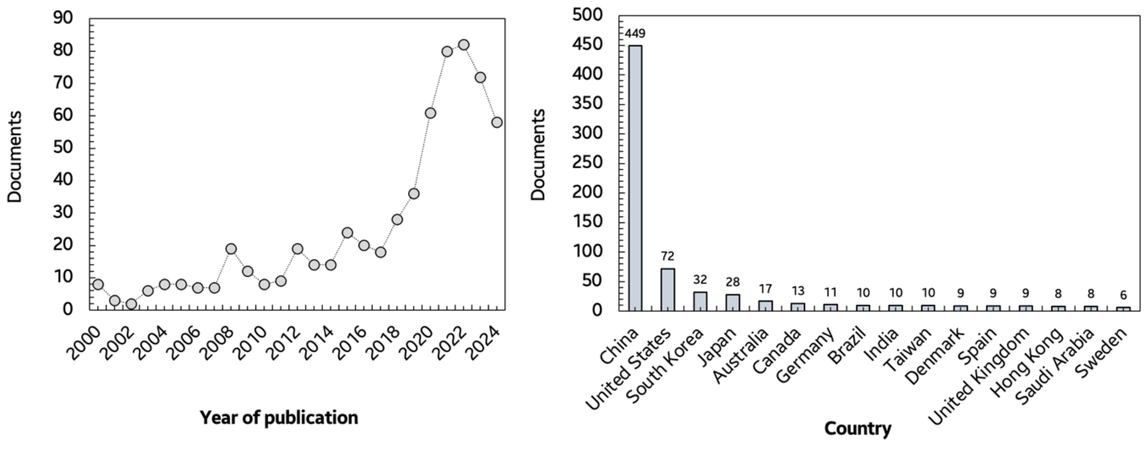
The results were synthesized and compared based on key areas of interest: the effects of biostabilization on physicochemical parameters (pH, moisture content, and organic matter) and the microbial community (diversity and pathogen reduction). The applications and limitations of various biostabilization methods were critically analyzed, offering a comprehensive perspective on the reviewed literature (Snyder, 2019).

3. Results

Articles published over the past 20 years were reviewed, beginning with the identification of 2,274 documents (100%) in the Scopus database. This initial set was subsequently reduced to 701 documents by applying a selection criterion of more than 30 citations (Figure 1). The percentage distribution of selected articles based on keywords was as follows: Swine manure composting (25.8%), Pig manure composting (28.06%), Pig manure biogas (15.17%), and Swine manure biogas (14.96%). Only open-access articles were included, resulting in a total of 58 selected documents.

In this study, the term swine waste was used to describe both residues with higher liquid content and those with a higher solids content. The term manure refers to the solid or semi-solid mixture of pig excrement combined with materials such as straw or wood residues. Meanwhile, pig slurry (also referred to as wet manure or swine slurry) denotes a liquid mixture of pig excrement containing approximately 9% total solids (TS) and a high proportion of water. This mixture is suitable for pumping and agricultural soil application and may also include undigested food residues (Fernández-Labrada et al., 2023).

Figure 1 - Scopus search results: Year and country distribution.



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4. Discussion

4.1 Characterization of Swine Waste

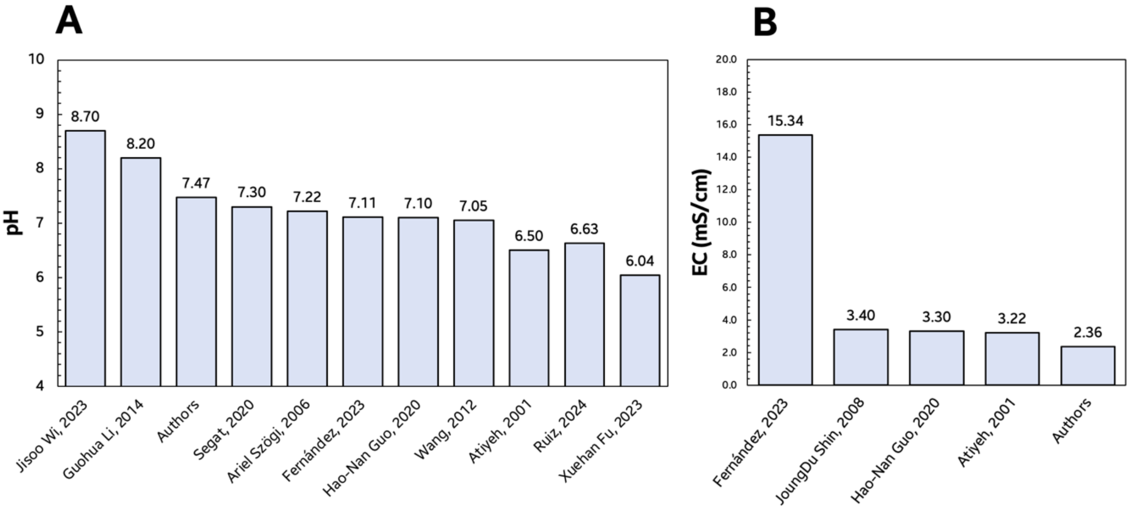
The composition of swine waste varies depending on feeding practices and production systems. Protein-rich and easily digestible diets, typical of monogastric species, directly influence fecal excretion. Both ruminants and monogastric animals excrete nutrients and organic matter through urine and feces. Urine, which is rich in N, P, and K not absorbed by animal tissues, mixes with feces, which contain cellular material from the digestive system, microorganisms, and unassimilated nutrients (Jensen et al., 2013).

The pH values of swine manure and slurry reported in various studies over the past 24 years are presented in Figure 2A. The data reveal a pH range between 6.0 and 8.8, reflecting variability likely influenced by differences in conditions or treatments applied in each case, with no clear temporal trend observed. From the 11 selected studies, an average pH of 7.45 was calculated.

The pH of pig slurry is a critical factor influencing both biological and chemical processes. However, variations in pH measurements and potential calculation errors are often attributed to the biotransformation of nitrogenous compounds, which act as pH buffers (Jensen et al., 2013). In the context of swine waste treatment for methane production, acidic pH levels inhibit the process, as the activity and growth of methanogenic bacteria decline significantly at pH < 7.0. Conversely, pH levels > 8.0 impair acidogenesis, reducing the efficiency of digestion (Lourinho et al., 2020).

Electrical conductivity (EC) values are presented in Figure 2B, showing considerable variability, with an average value of 2.30 mS cm-1. This variability indicates that multiple complex factors influence both pH and EC. Conductivity, which is directly related to ion concentration, may affect pH through acid and base dissociation processes driven by the high ionic strength of swine slurry (Jensen et al., 2013). Consequently, the application of these wastes to soils with high salinity sensitivity must be carefully managed due to the elevated salt content of swine waste.

Figure 2 - Measurements of (A) pH and (B) EC in pig manure and slurry in the last 24 years.



Source: Authors.

The organic matter (Figure 3A) in swine waste exhibits significant variability, with percentages ranging from 10% to 80%, and an average value of 39.89%. This suggests that the composition of organic matter in swine waste varies considerably, influenced by factors such as the pigs' diet, management practices, and other environmental conditions.

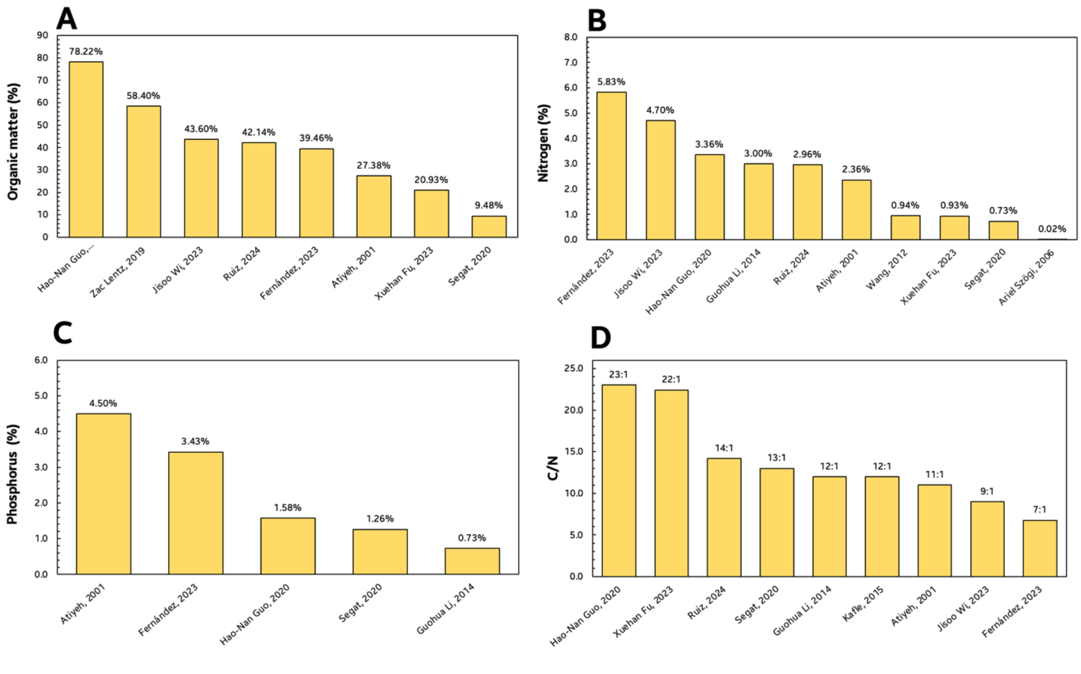
The total nitrogen content (Figure 3B) exhibits considerable variation, with values ranging from less than 1% to approximately 5%, and an average value of 2.51%. Phosphorus (Figure 3C) shows variable concentrations in the manure, with values fluctuating between 0.60% and 4.50%, and an average value of 1.73%, derived from the five selected studies. When utilizing these wastes, it is important to consider that excessive accumulation of P and N in soils, resulting from the application of pig waste, significantly increases the risk of runoff and leaching. This can trigger eutrophication processes in nearby water bodies, negatively impacting aquatic biodiversity and the quality of water for human consumption.

The C/N ratio (Figure 3D) exhibits a wide range of values, suggesting variability in the organic matter composition of the samples. Among the nine selected studies, the minimum value observed was 7:1, the maximum was 23:1, and the average was 15:1. Over 90% of the selected studies reported C/N ratios above 10:1. Anaerobic digestion requires an optimal C/N ratio to ensure process efficiency. While a range of 16:1 to 25:1 is recommended for anaerobic digestion, swine waste typically exhibits an imbalance, with an average C/N ratio of 15:1 (Kafle & Chen, 2016; Kumara & Varma, 2016). Such imbalances in the C/N ratio can lead to excessive formation of volatile fatty acids (VFAs) and total ammonia, both potent inhibitors of the digestion process (Lourinho et al., 2020). To address this deficiency and promote biodegradation, it is essential to incorporate organic materials (e.g., food waste or agricultural residues) that increase the carbon content and balance the C/N ratio, thereby optimizing anaerobic digestion.

In the anaerobic digestion process, the interaction between microorganisms and factors such as temperature, pH, alkalinity, volatile organic acids (VFA), long-chain organic acids, ammonia concentration, presence of heavy metals, detergents, antibiotics, nutrients, C/N ratio, organic load, retention time, agitation, total solids, and moisture content are critical (Domingues et al., 2021; Matiz-Villamil et al., 2023). Ammonia, which is toxic to methane production at concentrations exceeding 1.7 g L^{-1} of total ammonia nitrogen (TAN), becomes more toxic at higher pH levels and can destabilize the process by generating VFAs and reducing methanogenic efficiency (Chen et al., 2008).

The concentration of nutrients, pathogens, and other contaminants varies significantly depending on the animal diet, production system, and other pig management factors. In this context, designing an effective treatment for swine waste that enables its reuse as a fertilizer is crucial to preventing environmental and public health issues.

Figure 3 - Data measurements of (A) organic matter, (B) total nitrogen, (C) total phosphorus, (D) C/N ratio of pig manure and slurry in the last 24 years



Source: Authors.

4.2 Direct Application to the Soil

Although the direct application of pig manure or slurry to soil can provide agricultural benefits, such as nutrient supply and soil structure improvement, its environmental and health impacts depend on careful management to prevent nutrient overload, greenhouse gas emissions, soil degradation, pathogen introduction, and associated health risks (Chen et al., 2019; Rayne & Aula, 2020). High doses of pig slurry can increase phosphorus runoff, exacerbating water pollution issues (Huang et al., 2004). Furthermore, the application method (surface vs. injection) significantly influences greenhouse gas emissions, with injection techniques generally being more effective in reducing emissions compared to surface application (Francisco et al., 2021; Mecabô Júnior et al., 2024).

The growing concerns about public and animal health have brought the risks associated with swine waste to the forefront of debate. These wastes are a significant source of environmental pollution, as they harbor antibiotic-resistant pathogens (Sylvestre et al., 2014; Qian et al., 2018) and gastrointestinal parasites. The latter cause diseases, particularly in tropical regions, leading to substantial losses in swine productivity. These include poor feed conversion, stunted growth, intestinal malabsorption, weight reduction, delayed or incomplete immunity following vaccinations, negative impacts on meat quality, and a zoonotic risk to public health (Bawm et al., 2024).

It has been reported that pig feces contain oocysts of parasitic protozoa such as *Eimeria* sp., *Balantidium coli*, and *Giardia* spp (Ahmed et al., 2020; Chaudhary et al., 2023). Additionally, nematode eggs, including *Ascaris* sp. and *Trichuris* sp., as well as trematode eggs (*Dicrocoelium dendriticum*, *Fasciola* sp.), have also been identified (Wang & Davis, 2020; Class et al., 2022; Beily et al., 2023; Boyko et al., 2024). In terms of human health impact, pigs have traditionally been considered the primary reservoir of *Balantidium coli*, representing the most common source of infection (González de Canales Simón et al., 2000; Symeonidou et al., 2020). Although some parasites exhibit resistance to environmental changes, studies have shown that biological processes such as composting and anaerobic digestion can remove over 90% of helminth eggs and total coliforms (Qian et al., 2018; Boyko et al., 2024).

Table 1 summarizes key findings regarding the presence of parasites in swine fecal samples, along with the total and fecal coliform counts before and after biological stabilization processes.

Table 1 - Biological characterization of pig waste.

Country	Bacteria	Parasites	Results	Reference
Myanmar	-	*Ascaris suum* (34.8%) *Strongyloides* spp. (29.6%) *Trichuris suis* (21.4%) *Metastrongylus* spp. (20.0%) *Hyostrongylus* spp. (4.0%) *Fasciolopsis* spp. (1.6%) *Paragonimus* spp. (1.0%) *Schistosoma* spp. (1.0%)	Analysis of fresh stool samples	Bawm et al., 2024
Nepal	-	*Eimeria* sp. (26%), *Entamoeba coli* (25.5%) *Coccidia* (29%) *Ascaris suum* (32.5%) *Trichuris suis* (30%) *Fasciola* sp. (17.5%) *Physaloptera* sp. (17.5%) *Strongyloides* sp. (17.5%) *Metastrongylus* sp. (8%) *Oesophagostomum* sp. (5.5%)	Analysis of fresh stool samples	Chaudhary et al., 2023

Spain	Total coliforms: 10^9 MPN $(100\ mL)^{-1}$	9.27 Helminth eggs g^{-1} TS	Swine wastewater Aerobic and anaerobic reactors Helminth egg removal was 96.44%	Sylvestre et al., 2014
Canada	Total coliforms 5.53 log10 CFU g^{-1} Wet manure Fecal coliforms 5.27 log10 CFU g^{-1} Wet manure	-	Presence of antibiotic resistance genes in tomato, cucumber, pepper, carrot, radish, lettuce grown with pig manure	Marti et al., 2013
USA	Total coliforms: 6.79 log10 CFU mL^{-1} Fecal coliforms: 6.23 log10 CFU mL^{-1}	-	Liquid manure Nitrification-denitrification Solid-liquid separation reduced by 0.5-1.0 log10. Biological nitrogen removal reduced *Salmonella* by 2.4 log10	Vanotti et al., 2005

Source: Authors.

The indiscriminate use of antibiotics in livestock has contributed to the proliferation of ARGs, an emerging contaminant that, when present in manure used as fertilizer, accumulates in agricultural soils. This accumulation facilitates the dissemination of resistant bacteria and increases the risk of human exposure through water, soil, contaminated food, and airborne particles (Brooks et al., 2014; Sui et al., 2016; Yang et al., 2020). The agricultural application of swine manure, rich in ARB and plasmids carrying ARGs from the prophylactic use of antibiotics in animal production, can promote the horizontal transfer of ARGs to soil microbiota and pathogens, thereby elevating the risk of environmental contamination and public health issues related to food consumption (Marti et al., 2013; Zalewska et al., 2021; Hall et al., 2021).

Coliform bacteria capable of surviving and resisting multiple antibiotics, including amoxicillin-clavulanic acid, ampicillin, cefoxitin, chloramphenicol, nitrofurantoin, cotrimoxazole, and chlortetracycline, have been detected in vegetables (Marti et al., 2013). As shown in Table 2, several studies have tracked the transfer of ARGs from swine waste to the environment, highlighting the prevalence of tet, sul, and erm genes in fertilized soils (Chen et al., 2007; Selvam et al., 2012; Han et al., 2021). Although wastewater treatment and composting processes reduce ARG concentrations, they do not eliminate them entirely (Selvam et al., 2012; Sui et al., 2016).

Table 2 - Antibiotic resistance genes in studies on the treatment of pig waste in various countries.

Country	**Resistance genes**	**Related antibiotics**	**Reference**
Poland	*tetM, tetW, tetQ, blaSHV, blaTEM, blaCTX–M*	Tetracyclines, colistin, amoxicillin, ciprofloxacin, sulfamethoxazole	Zalewska et al., 2021
China	*sul*1, *sul*2, *tet*O, *tet*Q, *tet*W, *intl*1, *intl*2, bla_{OXA-1}, bla_{TEM-1}, bla_{ampC},	Tetracycline	Han et al., 2021
USA	*erm(B), erm(C), erm(F), erm(O), tet(Q), tet(X), intI1*	Chlortetracycline, lincomycin	Hall et al., 2021
China	*tetQ, sul1, qnrS*	Tetracyclines, sulfonamides, quinolones, macrolides	Yang et al., 2020
China	*tetX, ermF, ermB, mefA, tetM, sul2*	Tetracycline, macrolides, sulfonamides	Sui et al., 2016
USA	*tetA, tetB, mecA, ermF*	Tetracycline, macrolides, methicillin	Brooks et al., 2014

Source: Authors.

4.3 Stabilization of Swine Waste

Stabilization is a process in which swine manure is treated using physical, chemical, or biological methods to reduce its contamination potential, minimize odors and pathogens, and enable efficient reuse of swine waste. This process focuses on nutrient recovery, pathogen inactivation, and environmental sustainability.

4.3.1 Physical-chemical stabilization

The physicochemical treatment of swine waste involves the separation of nutrients or the transformation of the material through processes such as chemical precipitation, filtration, centrifugation, drying, and high-temperature thermal treatment (Çelen et al., 2007; Lang, Zhang, et al., 2019). Alkaline stabilization, achieved by adding calcium or potassium hydroxide to achieve a pH range of 11–13, effectively eliminates pathogens such as coliforms and fecal streptococci, while also reducing unpleasant odors, thus meeting Class B standards established by Part 503 US EPA regulations (Wong & Selvam, 2009). Hydrothermal carbonization (HTC) of swine manure, performed at temperatures between 180 and 250 °C, converts wet manure into hydrocarbons and process water, enhancing energy recovery and reducing environmental impacts by generating highly stable hydrocarbons enriched in soluble organic matter and essential macronutrients (Ipiales et al., 2024; Lang, Chen, et al., 2019).

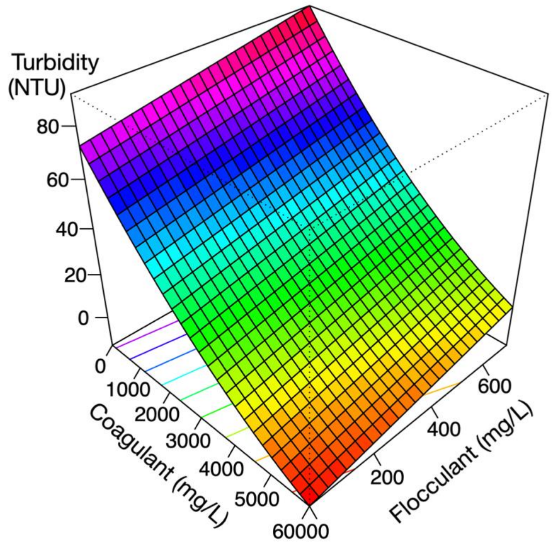
Struvite and hydroxyapatite are byproducts generated during the removal of phosphorus from swine wastewater, produced through precipitation processes with Mg^{+2} and NH_4^+ until a 1:1:1 molar ratio with the anion PO_4^{3-} is achieved (Chen et al., 2008). Phosphorus, an essential nutrient for plants and a key component of fertilizers, can be recovered through struvite crystallization, a process of significant importance for agricultural applications. This is particularly relevant as phosphorus is a non-renewable resource with limited availability for agriculture (Jokkaew et al., 2022; Korchef et al., 2023; McIntosh et al., 2022).

Solid-liquid separation, commonly used to reduce the water content in manure and concentrate nutrients, is notable for its low cost in filtration processes. However, it has limitations in retaining phosphorus particles and dissolved nutrients in the liquid phase (Jensen et al., 2013; Owusu-Twum & Sharara, 2020). The formation of a filtration cake, however, helps retain some of these particles, thus enhancing efficiency when coagulants such as aluminum sulfate, polyaluminum chloride, or ferric chloride, along with organic flocculants, are added prior to filtration (El Bied, García-Valero, et al., 2021).

Screw presses dehydrate the solid fraction, achieving a high concentration of dry matter. However, their low efficiency in separating nutrients such as N, P, and K arises from the pressure applied, which allows small particles to pass through the filter pores, concentrating them in the liquid fraction after separation (Varma et al., 2021). As a result, the solid fraction obtained has a low content of plant nutrients but is rich in organic matter and contains a low water content.

Coagulation-flocculation has proven effective for the removal of suspended solids, colloids, and nutrients, optimizing the solid-liquid separation in swine slurry, where most nutrients are present in particles smaller than 0.5 mm (Fragoso et al., 2015). For instance, a 99% reduction in turbidity was achieved in pig slurry using a dose of 0.024 mol L^{-1} (3892.9 mg L^{-1}) $FeCl_3$, combined with 0.1649 mL L^{-1} of cationic flocculant and an initial pH of 7.5 (El Bied, Kessler, et al., 2021). In Figure 4, the authors present the results of their laboratory experiments with swine wastewater. The study investigated the addition of aluminum polychloride (PAC) at doses ranging from 1000 to 6000 mg L^{-1} and anionic polyacrylamide (PAM) flocculant at doses ranging from 100 to 600 mg L^{-1}. The figure illustrates the reduction in turbidity, starting from an initial turbidity of 90 NTU in the wastewater.

Figure 4 - Effect of the concentration of PAC coagulant and PAM flocculant on the turbidity of swine wastewater.



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4.3.2 Biological stabilization

Biological stabilization processes, such as composting, are commonly used, often incorporating a co-substrate, such as a carbon-rich fibrous plant residue, to achieve a mixture with a moisture content of up to 60%, a C/N ratio between 25:1 and 30:1, and a structure conducive to aerobic decomposition under mesophilic or thermophilic conditions (Qian et al., 2014; Tiquia, 2005; Owusu-Twum & Sharara, 2020). However, the addition of a co-substrate like sawdust to pig manure with an initially low C/N ratio can reduce the amount of sawdust required but would necessitate a composting period of over 63 days (Huang et al., 2004). The World Health Organization recommends maintaining a temperature above 55°C for more than one week during thermal treatment of compost to ensure safe sanitization of the material (Jensen et al., 2013). A major drawback of composting is nutrient loss, particularly nitrogen, which can be significant during the composting of manure, with over half of the total nitrogen content lost due to NH_3 volatilization, leading to foul odors (Tiquia et al., 2002). According to studies referenced in Table 3, both aerobic and anaerobic systems are employed under mesophilic (up to 35°C) and thermophilic (55–65°C) temperatures, with pH values reaching up to 8.5, resulting in a significant reduction of up to 98.4% of ammoniacal nitrogen and chemical oxygen demand (COD).

Anaerobic digestion is a biological process in which microorganisms break down biodegradable material in the absence of oxygen, producing biogas with an energy content of 500–600 BTU per cubic foot (Kumara & Varma, 2016; Palmer, 1981). In the case of manure, the resulting biogas consists of 40–75% methane (CH_4), 40–50% carbon dioxide (CO_2), and approximately 1% hydrogen sulfide, ammonia, and other trace gases, making it suitable for electricity generation, heat production, or renewable fuel synthesis (Domingues et al., 2021). A 68-kg pig generates approximately 4.5 kg of slurry daily, containing 7% volatile biodegradable solids, of which 40–60% are digested over a period of up to 18 days, releasing approximately 0.42 m^3 of CH_4 per kilogram of volatile solids (Kumara & Varma, 2016). For efficient biogas production, it is recommended that the total solids concentration range between 8-12%, with 8% volatile solids for thermophilic digesters and 7-8% for mesophilic digesters (Sivamani et al., 2021).

The degradation of organic matter in anaerobic treatment does not generate excess heat, as the energy from the components is primarily directed toward methane production during methanogenesis (Jensen et al., 2013). This final phase of

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anaerobic digestion involves methanogenic microorganisms, which produce CH_4 from the end products of acetogenesis and some intermediates from hydrolysis and acidogenesis. Methanogens, obligate anaerobic archaea, are classified into five phylogenetic orders: Methanosarcinales, Methanobacteriales, Methanomicrobiales, Methanococcales, and Methanopyrales.

Anaerobic digestion offers several advantages, including low energy consumption, minimal space requirements, and relatively low construction costs. Additionally, it significantly contributes to reducing greenhouse gas emissions, unpleasant odors, and pathogens (Sousa et al., 2024). However, the process is not without challenges, as it requires a pre-treatment of organic waste, which demands thermal or mechanical energy (González-Fernández et al., 2008).

Table 3 - Stabilization operation conditions.

Country	Type of reaction	Operating conditions	Results	Reference
Germany	Anaerobic fixed-bed and expanded granular-bed reactors	Organic Load = High Retention = 30 days	CH_4 = 3 $m^3 m^{-3} d^{-1}$ in 2 days. The COD concentration of the filtered slurry used was 21.5 g/L. The reactor was more efficient with organic load > 4.32 g COD $L^{-1}d^{-1}$ (HRT = 5.9 days)	Häner et al., 2022
Spain	Anaerobic Reactor (CSTR)	Volume = 50 L, Temperature = 18-25 °C TRH = 8 hours Organic load = 1.0-3.5 kg DQO $m^{-3} d^{-1}$	High efficiency in COD and nutrient removal (90-95%). 72.0% acetic acid removal. Anaerobic treatment can be improved by reducing NH_3 concentrations by membrane extraction	Rivera et al., 2022
Japan	Fixed-bed anaerobic bioreactor	Use of Modified Porphyritic Andesite (WRS) as an Ammonium Adsorbent and Bedding Material T = 35°C HRT = 44 days Additive =$CaCl_2$	The bioreactor with WRS showed the best performance. CH_4 = 359.71 mL g^{-1} VS. Elimination of COD of 67.99%	Wang et al., 2012
Spain	Aerobic granular SBR reactor	Volume = 100 L Operating cycles = 3 h Volumetric exchange = 50% HRT = 6 hours Aeration = 65-80 L min^{-1} Temperature = 18-22 ºC	Formation of granules from 1.8 mm to 3.4 mm. Effective removal of organic matter and N The removed OLR was 5 kg COD $m^{-3} d^{-1}$ and the NLR was 0.15 kg N $m^{-3} d^{-1}$	Morales et al., 2011
Spain	Granular aerobic reactor	Granular Sequencing Batch Reactor V = 1.5 L Height/Diameter = 5.5 Substrate = Highly loaded pig slurry	Organic matter removal efficiencies of up to 87%. N removal efficiencies of up to 70% during the treatment of organic and N loading rates (OLR and NLR) of 4.4 kg COD $m^{-3} d^{-1}$ and 0.83 kg N $m^{-3} d^{-1}$	Figueroa, 2011
Spain	Sequential Batch Reactor (SBR) Nitrification Denitrification	Volumen = 20 L Temperatura = 20°C pH = 8,01 Dissolved oxygen = 3 mg/L	Nitrogen removal 45% of the total organic substrates were aerobically biodegradable. 75% of the oxygen needed to complete the oxidation of ammonium	Magrí et al., 2008
USA	Sequential Batch Reactor (SBR) - Anaerobic/Anoxic Nitrification	T = 20°C Cycles = 8 hours per cycle, Hydraulic retention time = 3.3 days Acetate Addition	Nutrient removal. With the addition of acetate: 100% removal of ammonia nitrogen. Removal of 98.7% of total nitrogen and 97.4% of COD	Zhu et al., 2006

Source: Authors.

4.4 Challenges

The challenges associated with traditional swine waste stabilization, such as low energy efficiency and the generation of lower-quality by-products, have driven the search for innovative alternatives, with co-digestion standing out as a promising approach.

Anaerobic co-digestion, a technique that combines various organic wastes in the digestion process, provides a more efficient and sustainable solution for waste management by maximizing biogas production, improving digestate quality, and stabilizing the process. This is achieved through enhanced biodegradability and optimal nutrient balance compared to the digestion of a single substrate (González et al., 2022; Kadam et al., 2024; Zhang et al., 2021). Although a C/N ratio of 20:1 to 30:1 is typically used to determine the co-substrate ratio, the stability and success of anaerobic co-digestion depend on a combination of factors, including the specific characteristics of the co-substrates (Chuenchart et al., 2024). Therefore, the ideal co-substrate ratio for maximizing methane production is influenced by the macromolecular and fiber composition, nutrient profile, and the presence or generation of potential inhibitors, such as long-chain fatty acids, hydrogen sulfide, ammonia, humic acid, and dissolved lignin (Chuenchart et al., 2024; Karki et al., 2021).

It is important to emphasize that the relationships between co-substrates and swine waste vary depending on the total solids content. For instance, in the case of a swine wastewater mixture, as detailed in Table 4, co-digestion is most effective with a 1:3 ratio of co-substrate to wastewater for methane production (Sousa et al., 2024; Tian et al., 2023). In contrast, for manure, a higher amount of co-substrate is required, such as rice and corn straw (Song et al., 2016; Tian et al., 2023). Notably, the co-substrate to waste ratio depends on the type of co-substrate, as it influences the biogas production rate, chemical oxygen demand (COD) removal, and volatile solids (VS) degradation.

Table 4 presents studies that utilized organic co-substrates, including corn, rice, rapeseed residues, and oils, maintaining temperatures of 35-37°C in mesophilic systems and 55°C in thermophilic systems, with a pH range of 6.5 to 8.2. The average methane production ranged from 0.22 to 0.65 m^3 CH_4 kg^{-1} VS. Retention times were 12-18 days for mesophilic digesters and 5-6 days for thermophilic digesters. Ammonia inhibition was not observed when its concentration was maintained below 300 mg $N\text{-}NH_4$ L^{-1}. Co-digestion with substrates such as oils and agricultural residues enhances the efficiency of the process. Monitoring volatile solids and organic acid levels is crucial to prevent inhibition and improve overall performance.

In addition to biogas, the anaerobic digestion of pig manure generates byproducts such as digestate, a nutrient-rich residual material (N, P, and K) that can be utilized as an organic fertilizer (Samoraj et al., 2022; Sousa et al., 2024). This digestate can be separated into a solid fraction, suitable for soil conditioning, and a nutrient-rich liquid fraction, which serves as a liquid fertilizer.

While anaerobic co-digestion offers benefits such as enhanced biogas production efficiency and improved process stabilization, the selection of incompatible substrates may lead to nutritional imbalances (Chuenchart et al., 2024). Although the appropriate combination of substrates can result in more balanced nutrient profiles, in some cases, composted pig waste fails to effectively reduce the presence of ARGs (Peng et al., 2015).

Table 4 - Methane production from the co-digestion of pig waste based on co-substrates and operating conditions.

Country	Co-substrate type	Operating conditions	Results	Reference
Brazil	Food waste (FW), grass residue (GR), poultry litter (PL)	Swine wastewater (SW) VS/TS = 0.70 pH = 6.0-8.0 T = 35°C Alkalinity > 3,0 g $CaCO_3$ L^{-1}	Methane production Mix 1:3 (GR:SW) = 237.47 mL CH_4 g^{-1} VS Mix 1:3 (FW:SW) = 263.21 mL CH_4 g^{-1} VS	Sousa et al., 2024
China	Rice straw	Manure C/N = 8.18 VS/TS = 78.37 pH = 7.86 T = 37°C 12% TS	Methane production Mix 5:1 (Straw:Manure) 481.48 mL CH_4 g^{-1} VS	Tian et al., 2023
China	Domestic sewage sludge	Manure TS = 31.97% VS/TS = 63.06 C/N = 20.70 pH = 8.58	Methane production Mix 1:2 (Sewage:Manure) 264.39 mL CH_4 g^{-1} VS	Zhang et al., 2021
Brazil	Waste cooking oil	Concentrations of waste cooking oil: up to 69.4 g of residual oil per kg of manure.	Methane production Optimal mixing: 45.6 - 66.7 g oil per kg manure Yield = 0.29 m^3 Kg^{-1} VS VS reduction (51.4%) with 54.6 g of residual oil per kg of manure	Sunada et al., 2018
China	Corn straw	Manure pH = 7,0 T = 35°C 30 days Alcalinidad = 3,6 g/L	Methane production Mix 2:1 (Straw:Manure) Yield = 0.295 m^3 Kg^{-1} VS. There were no significant changes in pH (6.6-8.2). Pathogen reduction	Song et al., 2016
Spain	Used vegetable oils, pig manure	Mesophilic temperature (37°C). HRT = 4 days (acidifier) and up to 20 days (methanizer)	Methane production Yield = 0.65 m^3 Kg^{-1} VS. COD removal = 86.4% and TDS = 81.9% at 20 days of HRT	Hidalgo et al., 2015
China	Rice straw	Manure C/N = 35-40 T = 30°C Mix every 10 days	Composting 40% Straw + 60% Est. Mix 1:1.5 (Straw:Manure) Maturation at 90 days	Qian et al., 2014
Spain	Corn, rapeseed and sunflower residues	Semi-continuous flow 35°C, pH = 7.9 Time = 30 days Alcalinidad = 18.1 g L^{-1} C/N = 64.7	Yield = 0.34 m^3 Kg^{-1} VS day was obtained by codigesting rapeseed residues	Cuetos et al., 2011

Source: Authors.

5. Conclusions

The variability in the composition of organic matter, nitrogen, and phosphorus in swine waste significantly influences its management and use as fertilizer. An appropriate treatment is crucial to prevent environmental and public health issues. Although the direct application of slurry provides agricultural benefits, its impact is contingent on careful management to prevent water contamination, greenhouse gas emissions, pathogens, and antibiotic resistance genes. Physicochemical and biological treatments, such as chemical precipitation, coagulation-flocculation, composting, and anaerobic digestion, enhance efficiency and yield valuable byproducts, with anaerobic codigestion standing out for its efficiency and stability in biogas production.

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